NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

SUBMARINE BASE, GROTON, CONN.

REPORT NUMBER 1117

DISCRIMINATION AND IDENTIFICATION OF
MODULATION-FREQUENCY USING NOISE, TONE, AND TONAL-COMPLEX CARRIERS

by

Thomas E. HANNA

Office of Naval Research
61153N 42 RR04209 RR0420901 4424207

Released by:

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Naval Submarine Medical Research Laboratory
23 May 1988

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS N.A.
2a. SECURITY CLASSIFICATION AUTHORITY N. A.	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N. A.	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Naval Submarine Medical Research Laboratory Report Number	5. MONITORING ORGANIZATION REPORT NUMBER(S) Same
6a. NAME OF PERFORMING ORGANIZATION Naval Submarine Medical Research Laboratory 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research
6c. ADDRESS (City, State, and ZIP Code) Naval Submarine Base Box 900 Groton, CT 06349-5900	7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research 8b. OFFICE SYMBOL (If applicable) Code 1142PS	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N0001488WR24003
8c. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217-5000	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO.: 61153N 42 PROJECT NO.: RR 04209 TASK NO.: RR0420901 WORK UNIT ACCESSION NO.: 4424207

11. TITLE (Include Security Classification)
(U) Discrimination and identification of modulation frequency using noise, tone, and tonal-complex carriers

12. PERSONAL AUTHOR(S)
Thomas E. Hanna

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM ______ TO ______		

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Amplitude modulation; modulation frequency; identification; discrimination; auditory psychophysics

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A two-interval, two-alternative, forced-choice discrimination task (2I-2AFC) and an identification task were used to measure listeners' abilities to resolve modulation frequency, using three different types of carrier--noise, a 1-kHz tone, or a tonal complex. Identification performance was not simply related to 2I-2AFC discrimination performance. Identification of stimuli near the edges of the range was relatively good compared with listeners' abilities to discriminate these stimuli, a result which has been found for other stimuli (e.g., Berliner, Durlach, & Braida, 1977). In addition, certain midrange stimuli were identified relatively well, indicating the effects of central factors that enhance the encoding of these stimuli. Results for the 1-kHz and the tonal-complex carrier showed enhanced identification of modulation frequencies in the range 50-80 Hz. The results for the noise carrier, however, indicated enhanced resolution only for modulation frequencies less than 54 Hz. Possible explanations for these effects are discussed, and it is suggested that a more detailed examination of the role of the stimulus context would provide some answers.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL John J. O'Hare	22b. TELEPHONE (Include Area Code) (202) 696-4502 22c. OFFICE SYMBOL Code 1142PS

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

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Thomas E. Hanna

Naval Submarine Medical Research Laboratory
Naval Submarine Base New London
Groton, Connecticut

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Approved and Released by

C. A. Harvey

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SUMMARY PAGE

PROBLEM

To develop and apply a technique to identify those features that underlie the recognition of complex acoustic stimuli.

FINDINGS

Discrimination and identification performance were compared in order to measure peripheral and central limitations on listeners' abilities to resolve modulation frequency. The results showed that certain modulation frequencies were resolved better than others in the identification task. The frequencies that were identified best bore little relation to those that were discriminated best, indicating that central processes enhanced the encoding of certain modulation frequencies. The frequencies that were encoded best depended on the type of carrier. For a 1-kHz tone carrier and a tonal complex carrier, identification performance was best for modulation frequencies from 50-80 Hz. For the noise carrier, identification performance was best for modulation frequencies less than 54 Hz. The results are discussed in terms of the types of cues that are available for each of the carriers and the effects of the stimulus context. The theory of Durlach & Braida (1969) provides a useful framework for interpreting the results.

APPLICATION

These results provide a better understanding of the perceptual encoding of one aspect of the temporal envelope, modulation frequency, and the effects of the carrier type. The technique provides a framework for understanding the central encoding of an acoustic signal, which will help in understanding the recognition process.

ADMINISTRATIVE INFORMATION

This research was carried out under the Office of Naval Research 61153N42 RR04209 01 4424207. It was submitted for review on 14 Mar 88, approved for release on 23 May 88, and designated as NSMRL Report Number 1117.

PUBLISHED BY NAVAL SUBMARINE MEDICAL RESEARCH LABORATORY

ABSTRACT

A two-interval, two-alternative, forced-choice discrimination task (2I-2AFC) and an identification task were used to measure listeners' abilities to resolve modulation frequency using three different types of carrier-- noise, a 1-kHz tone, or a tonal complex. Identification performance was not simply related to 2I-2AFC discrimination performance. Identification of stimuli near the edges of the range was relatively good compared with listeners' abilities to discriminate these stimuli, a result which has been found for other stimuli (e.g., Berliner, Durlach, & Braida, 1977). In addition, certain midrange stimuli were identified relatively well, indicating the effects of central factors that enhance the encoding of these stimuli. Results for the 1-kHz and the tonal-complex carrier showed enhanced identification of modulation frequencies in the range 50-80 Hz. The results for the noise carrier, however, indicated enhanced resolution only for modulation frequencies less than 54 Hz. Possible explanations for these effects are discussed, and it is suggested that a more detailed examination of the role of the stimulus context would provide some answers.

INTRODUCTION

Recent research has emphasized the importance of the temporal envelope for recognition of complex auditory signals. For example, Van Tassell et al. (1987) have shown that temporal modulation cues in the range from 20 to 200 Hz can be used to encode phonetic features. Mackie et al. (1981) provide evidence that some perceptual dimensions of sonar signals are related to modulation in the temporal envelope of these signals. Our ability to enhance recognition of sonar signals and to develop classification algorithms would be greatly increased by an understanding of how human listeners derive distinctive information from a signal's temporal envelope.

The present research examines the perceptual encoding of one aspect of the envelope, modulation frequency. A basic constraint on our perception of modulation frequency is the limited resolution of the peripheral sensory system. The variability in the peripheral transduction of a modulated signal will limit the degree to which two signals with nearly equal modulation frequencies can be resolved. The sensory limitations on the perception of modulation frequency can be obtained from fixed-standard, two-interval, two-alternative forced choice discrimination tasks. These data have been collected using a tone carrier (Buus, 1983) and a noise carrier (Miller & Taylor, 1948; Ahroon & Fay, 1977; Formby,1985).

In addition to sensory limitations, there are more central limitations on the perception of modulation frequency. Recognition of signals involves more complex processing, such as the direction of attention under conditions where any of a large number of signals could occur, or the encoding of information in a form that can be compared to learned mental representations of auditory events. Data have not been collected to assess these more central limitations on the encoding of modulation frequency, for example, by using an identification task. Since we rarely are faced with auditory tasks where a minimal sensory discrimination provides the distinctive information used in making judgments, the use of an identification task should provide greater knowledge about features that underlie recognition of naturally occurring acoustic stimuli.

The present research measures both discrimination and identification performance in order to contrast the sensory (peripheral) and perceptual (central) representation of modulation frequency. Such data should provide a better understanding of the encoding process and help define distinctive features that underlie recognition of complex sounds. Different types of carrier are used to determine whether the encoding of envelope frequency is independent of other aspects of the signal.

EXPERIMENT 1: IDENTIFICATION AND DISCRIMINATION OF MODULATION FREQUENCY USING A NOISE CARRIER.

A. Method

Broadband noise was multiplied by a DC-offset sinusoid to produce essentially 100% amplitude modulated noise (peak-to-trough amplitude ratio of 60 dB). The modulated waveform was gated on and off with a 20-ms cosine-squared ramp to minimize gating transients. Total duration was 500 ms. The resulting waveform was bandpass filtered from 500-4000 Hz by a Wavetek Brickwall filter (Model 753A, asymptotic rejection rates of 115 dB/octave) and presented to the listeners at an overall level of 68 dB SPL over TDH-50P earphones. Three college students with normal audiograms served as listeners and were paid for their participation.

For the identification task, on each trial, the listener heard one of nine modulation frequencies -- 30, 36, 44, 54, 66, 82, 100, 122, or 150 Hz -- and he or she identified which of the nine had been presented. These values are approximately logarithmically spaced to reflect the fact that the difference limen increases with modulation frequency (Miller & Taylor, 1948). In each two-hour session, 15 blocks of 90 trials were presented, yielding 150 trials per modulation frequency per day. Two of the three listeners had four practice sessions and three test sessions; the third listener had two practice sessions and two test sessions.

After completion of the identification task, a discrimination task was used. Each trial consisted of two sequential stimuli, a standard fixed over a block of 40 trials and a comparison stimulus incremented by either 2, 4, 8, or 16 Hz. The two were presented in random order. The subject indicated which of the two was the incremented stimulus. Eight modulation frequencies, identical to those used in the identification experiment with the exception of 150 Hz, were used as the standard across blocks. Each two-hour session consisted of three sets of eight 40-trial blocks. Each of the eight standards was used once in each set. The order of the eight standards was randomized for each set. After two practice sessions, four or five sessions of data were collected for each standard, yielding 480 to 600 trials per standard for subsequent analyses.

B. Results & Discussion

A measure of sensitivity, d', was computed for both the identification and discrimination data. The data for the identification task were collapsed across blocks into a 9x9 confusion matrix. d' was calculated for the eight pairs of adjacent stimuli by further collapsing the confusion matrix into eight 2x2 matrices. The responses to adjacent stimuli i and i+1 were separately categorized as being greater than i or less than i+1. That is, the four cells of a given matrix were defined as: 1) an identification of stimulus i as i or a modulation frequency less than i, 2) an identification of stimulus i as i+1 or a modulation frequency greater than i+1, 3) an identification of stimulus i+1 as i or a modulation frequency less than i, and 4) an identification of stimulus i+1 as i+1 or a modulation frequency greater than i+1. For each matrix, a d' was computed by dividing the number of responses in category (1) by the number in [(1)+(2)] and treating it as a hit rate, and dividing the number of responses in category (3) by the number in [(3)+(4)] and treating it as a false alarm rate (Green & Swets, 1966/1974). This categorization of stimuli was judged to be appropriate given that no pronounced response biases were observed.

The data for the discrimination task were also collapsed across blocks. A d' was estimated for each combination of modulation frequency and increment. The d'-values were then fitted with a psychometric function of the form, $d'=a(\Delta f)$ for each standard. In order to compare the results with those from the identification task, for each standard, a d' was estimated for a value of Δf corresponding to the frequency separation used in the identification task. For example, the identification task had 30 and 36 Hz as adjacent stimuli. Thus, for the discrimination task, a d' was estimated for the 30 Hz standard and a 6 Hz increment.

The results for each of the three listeners plus the mean results are shown in Fig. 1 for both the identification and the discrimination task. For the identification data, d' is plotted as a function of the lower of the two adjacent modulation frequencies. For the discrimination data, d' is plotted as a function of the modulation frequency of the standard.

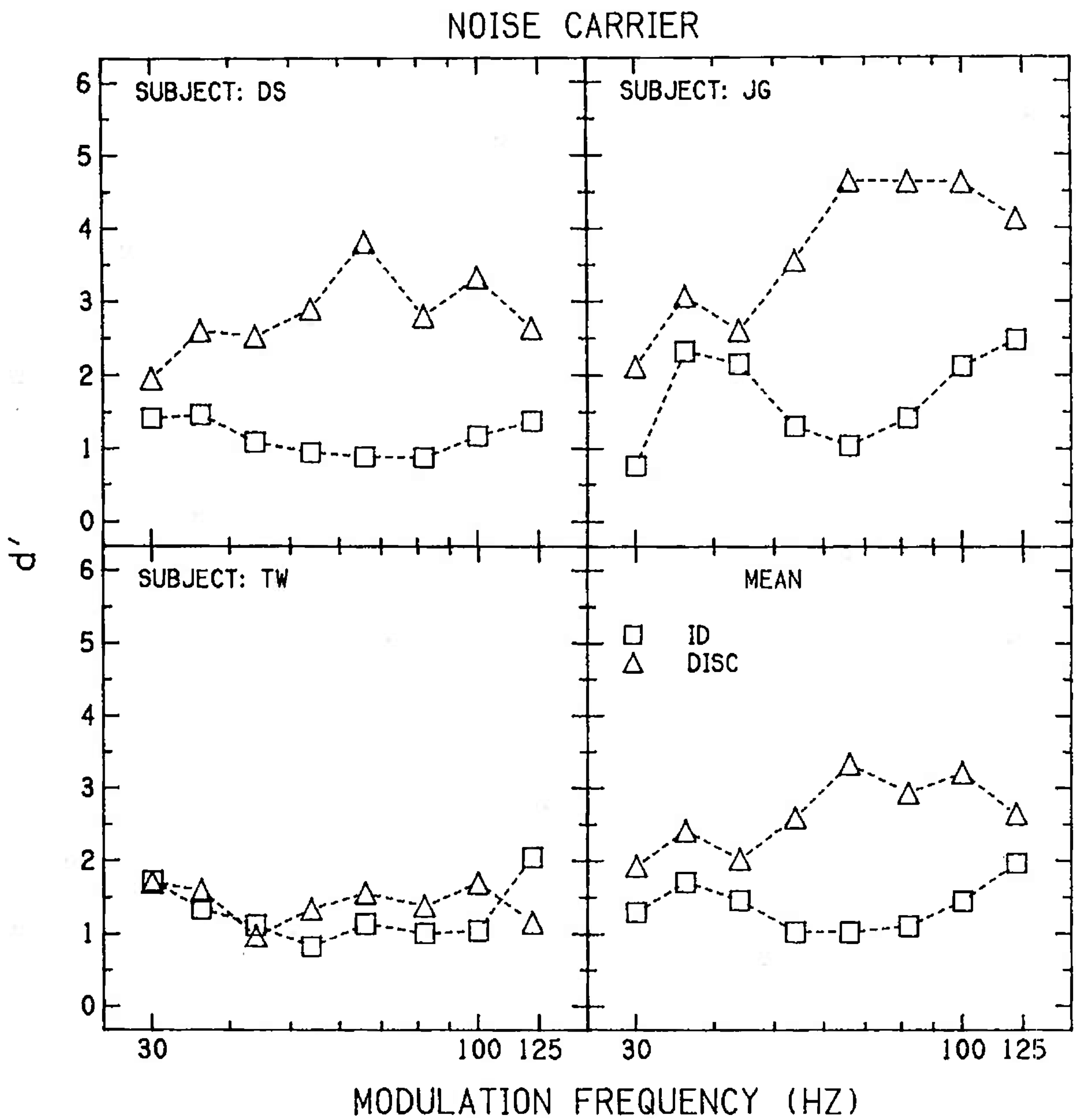

Figure 1. d' as a function of modulation frequency for the discrimination task (triangles) and the identification task (squares) for the noise carrier.

Discrimination was better than identification in virtually every case. Best identification performance was obtained for stimuli nearer the ends of the range of modulation frequency. For these frequencies, identification performance was almost as good as discrimination performance. This "edge effect" is commonly observed in identification tasks (see Berliner, Durlach, & Braida, 1977). For midrange frequencies, identification performance is noticeably worse than discrimination, reflecting the limitations of central processes in the encoding of these stimuli. These results also indicate that the stimuli at the lower end of the range are less affected by these additional sources of variability that limit performance in the identification task.

In Fig. 1, d' depends on the particular stimulus spacing used in the identification task. Figure 2 replots the data of Fig. 1, with the ordinate converted to the increment in modulation frequency needed to yield a d' of 1. Threshold, in Hz, is plotted as a function of modulation frequency. Such a conversion expresses sensitivity in absolute stimulus terms, Hz, which corrects for the fact that in Fig. 1 the stimulus increment increases with modulation frequency. The discrimination thresholds are comparable to those obtained by Miller & Taylor (1948). Average thresholds range from 3 to 14 Hz and tend to increase with modulation frequency. Average thresholds for identification range from 5 to 17 Hz, differing by a factor of three from the discrimination thresholds in the middle of the range. Average thresholds for the identification task asymptote at about 17 Hz, but this value might be dependent on the range and upper limit of modulation frequencies used.

Figures 1 and 2 indicate that identification is about as good as discrimination over the range from 30 to 54 Hz (keeping in mind that the data point plotted at a modulation frequency of 44 Hz represents discrimination of a 44 Hz modulation from a 54 Hz modulation). This result suggests that central encoding of lower modulation rates is better than that of higher rates. However, this observation may be influenced by the fact that the stimuli were logarithmically spaced and thus the lower range has a denser spacing. In fact, the 24-Hz range from 30 to 54 Hz is comparable in extent to the 28-Hz range from 122 to 150 Hz of the upper two stimuli. Thus, if the edge effect acts over a fixed frequency range, then the better relative performance at the lower frequencies may be due to the edge effect rather than to an inherent advantage for lower frequencies. Another way to consider the effect is that selective attention may operate over a fixed range of modulation frequencies; the particular spacing used favors an attentional focus at the lower end, because a greater proportion of the stimuli are included in a fixed range at that location.

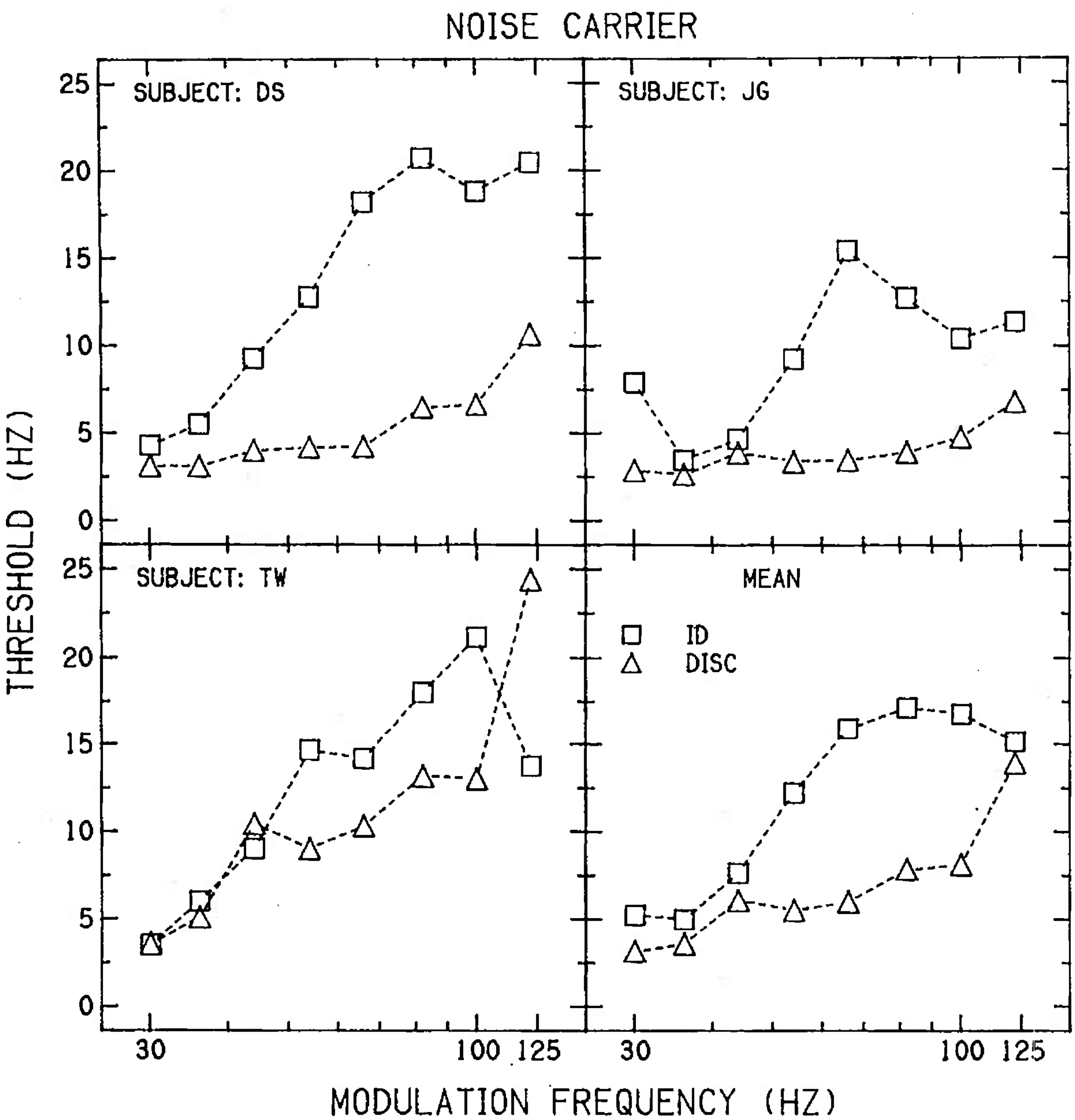

Figure 2. Threshold, in Hz, as a function of modulation frequency, in Hz, for the discrimination task (triangles) and the identification task (squares) for the noise carrier. The data in Fig. 1 have been converted to obtain the stimulus difference needed to yield a d' of one.

II. EXPERIMENT 2: EFFECTS OF CARRIER TYPE

Environmental stimuli differ in the type of carrier that is modulated. The first experiment used broadband noise as the carrier. The second experiment used a tone or a tonal complex as carriers to investigate the extent to which the resolution of modulation frequency depends on the type of carrier.

A. Method

Stimuli were generated digitally and presented over 16-bit digital-to-analog converters. Modulated 1-kHz tones were constructed by adding two tones with frequencies $1000-(\Delta f/2)$ Hz and $1000+(\Delta f/2)$ and starting phases of 90 and 270 degrees, respectively, producing a stimulus with a modulation frequency of Δf. Stimuli were gated on and off at envelope minima with a 20-ms cosine-squared onset and offset ramp. Total duration was 500 ms. The level of each of the two tones was 57 dB SPL. For a second set of conditions, modulated tonal complexes were constructed by adding 14 modulated tones, harmonics of 250 Hz from 500 to 3750 Hz, each constructed like the 1-kHz modulated tone. Thus, this stimulus consisted of 28 tones, arranged in pairs. The overall level was 50 dB SPL. Three new subjects participated in the experiment.

With modulated tones, it is possible that discrimination is based on the listener's ability to distinguish a spectral change in the individual components rather than a change in the envelope. Two-tone modulation was chosen to minimize this possibility and to produce the largest range of modulations while keeping the components within a critical band. For example, amplitude modulations of 90 and 100 Hz using three tones require a 180- and a 200-Hz separation, respectively, between the upper and lower tones, whereas using two tones requires only a 90- and 100-Hz separation. Buus (1983) has demonstrated that envelope frequency, rather than spectral change, is the basis for discrimination of modulation frequencies less than 100 Hz and carrier frequencies from 500 to 4000 Hz. Thus, it was felt that two-tone modulation would provide a good evaluation of sensitivity to envelope cues for the present study.

Four conditions were run: an identification task and a discrimination task for both the modulated 1-kHz tones and the modulated tonal complexes. The data for the tonal complex were collected first. For each carrier, the discrimination task was completed first.

For the discrimination task, each trial consisted of two stimuli, a standard fixed over a block of 40 trials and a comparison stimulus incremented in modulation frequency by either 2, 4, 8, or 16 Hz on each trial. The two stimuli were presented in random order and the subject indicated which was the incremented stimulus. Five modulation frequencies, 20, 40, 60, 80, and 100 Hz, were used as the standard across blocks. Three sets of five 60-trial blocks were run in each two-hour session. After two practice sessions, two test sessions were run, yielding 360 trials for each standard.

For the identification task, on each trial, the listener was presented one of nine waveforms, having a modulation frequency of 20, 30, 40, 50, 60, 70, 80, 90, or 100 Hz, and he or she identified which of the nine had been presented. These values were linearly spaced to reflect the fact that the difference limen is approximately constant over this range of modulation frequency (Buus, 1983). Ninety trials were presented within a block and fifteen blocks were completed in each two-hour session. Each of three listeners was given two practice sessions and one test session.

B. Results & Discussion

Data analyses were identical to those for Experiment 1. Figures 3a and 3b show d′ for the modulated tones and tonal complexes, respectively. As in Fig. 1, the lower functions represent the results for the identification task and the upper functions show the results for the discrimination task. As with the noise carrier, identification performance is best at the edges where it approaches that found in the discrimination task. For subject CM and the 1-kHz carrier, the identification d′s at the edges do not approach that for the discrimination task, perhaps due to limitations of the identification task for estimating large d′ values. However, contrary to the results with the noise carrier, a relative peak in identification performance is also found for a modulation frequency in the middle of the range. The results for individual listeners show peaks at modulation frequencies of 50 or 60 Hz for the modulated 1-kHz tone and 60 or 70 Hz for the modulated tonal complex. Figures 4a and 4b show the increment in modulation frequency needed to yield a d′ of one. Identification thresholds show a local minimum of 6-7 Hz in the midrange.

The reason that certain midrange frequencies are encoded better than the others is not evident, nor is it clear why these results should differ from those with a noise carrier, where frequencies less than 54 Hz were encoded best. One factor may be that the region from 50 to 80 Hz is the region of maximal roughness for tonal stimuli (see Plomp, 1976), which would provide a perceptual reference as do the edges of the frequency range.

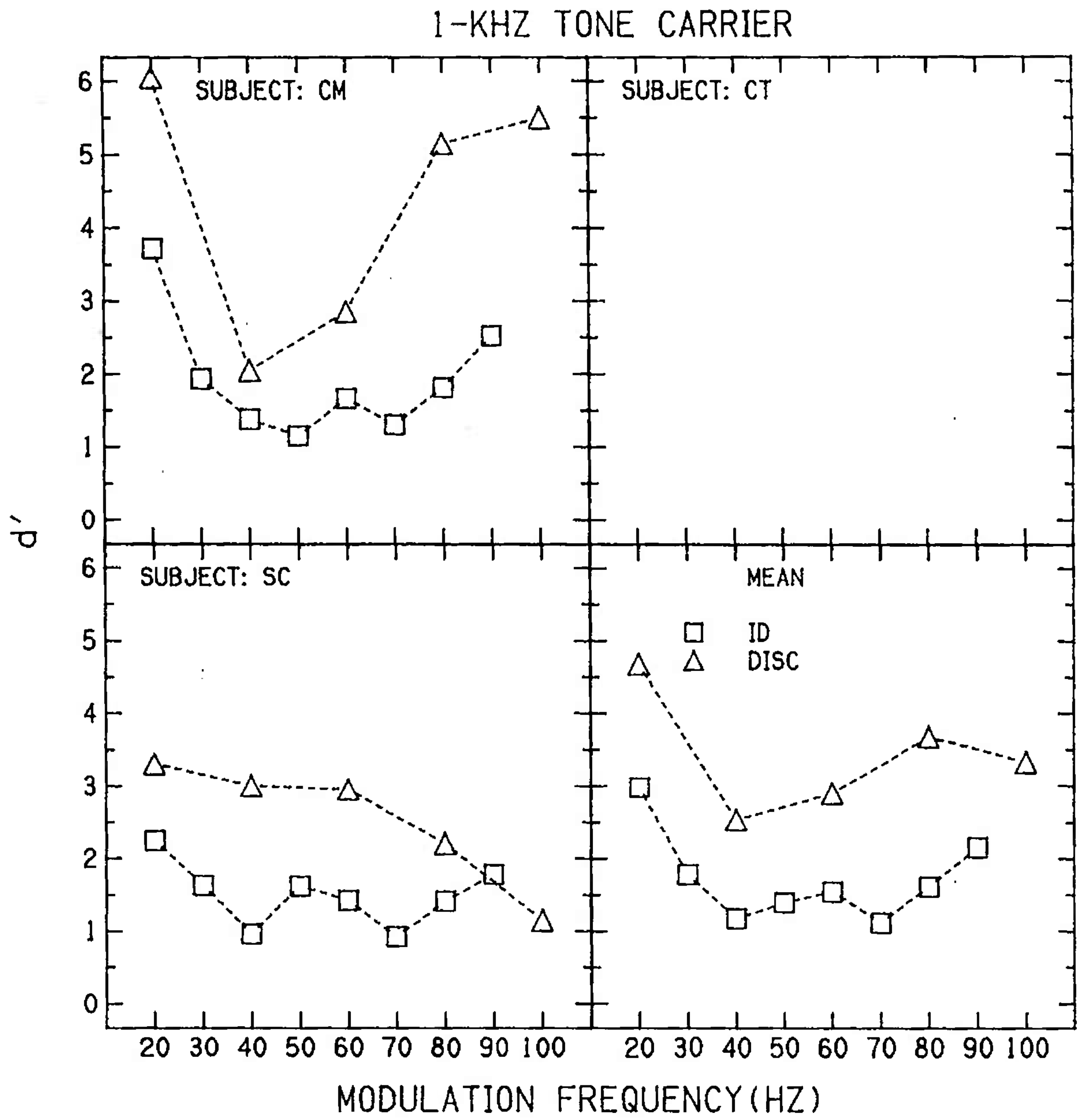

Figure 3a. d' as a function of modulation frequency for the discrimination task (triangles) and the identification task (squares) for the 1-kHz tone carrier.

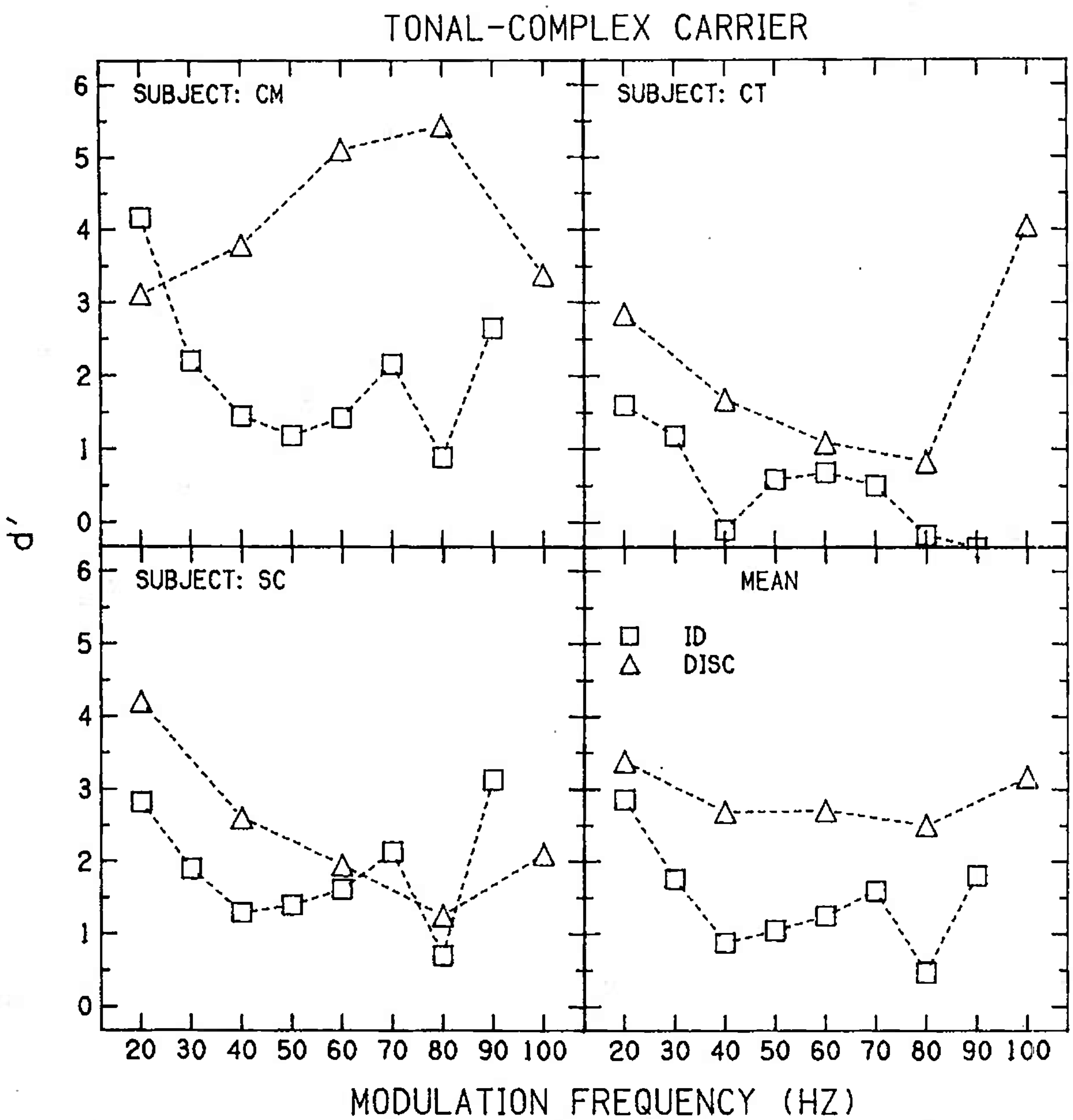

Figure 3b. d' as a function of modulation frequency for the discrimination task (triangles) and the identification task (squares for the tonal-complex carrier.

The average discrimination thresholds for the 1-kHz carrier (Fig. 4a) are about 3 Hz and agree well with those from comparable conditions (Buus, 1983). The discrimination thresholds for the modulated tonal complex ((Fig. 4b) are also about 3 Hz. These thresholds are similar to those obtained with the noise carrier at the lower modulation frequencies, at least for frequencies less than 70 Hz for two of the subjects. The apparent lack of dependence of discrimination thresholds on carrier type does not hold at higher modulation frequencies, where thresholds are higher with the noise carrier.

III. GENERAL DISCUSSION & SUMMARY

This experiment was an initial attempt to understand whether features of the temporal envelope are encoded for identification of complex signals. As was evident, resolution of modulation frequency in the identification tasks was not strictly proportional to resolution in the discrimination task. Central factors apparently determine which modulation frequencies are encoded most reliably beyond differences which can be attributed to the sensory system. Similar effects for speech stimuli have been demonstrated by Macmillan, Braida, & Goldberg (1987) (also see Macmillan (1987) for a more general discussion). Although certain aspects of that central encoding, such as edge effects, depend on the task, others, such as the better identification of particular midrange stimuli, seem to reflect an inherent property of the stimulus. In order to verify that these latter effects are attributable to the stimulus rather than to specifics of the task, future work might explore in detail the effects of the stimulus context.

The fact that different effects were observed with different carriers indicates that modulation frequency is not encoded independently of carrier. Discrimination thresholds did not differ appreciably among the three types of carrier below 70 Hz, but the identification thresholds did. They were best below 54 Hz with the noise carrier but best from 50 to 80 Hz with the tonal carriers. Part of these differences may be due to the differences in stimulus spacing. However, this explanation probably cannot account for the failure to find good identification in the region from 50 to 80 Hz with noise carriers. This result is most likely due to either the stochastic nature of the noise carrier, which may reduce a roughness cue available with nonstochastic carriers, or due to the presence of spectral or pitch cues with tonal carriers. The possibility of such factors and their resolution is important for better understanding the encoding of the temporal envelope and its dependence on the carrier.

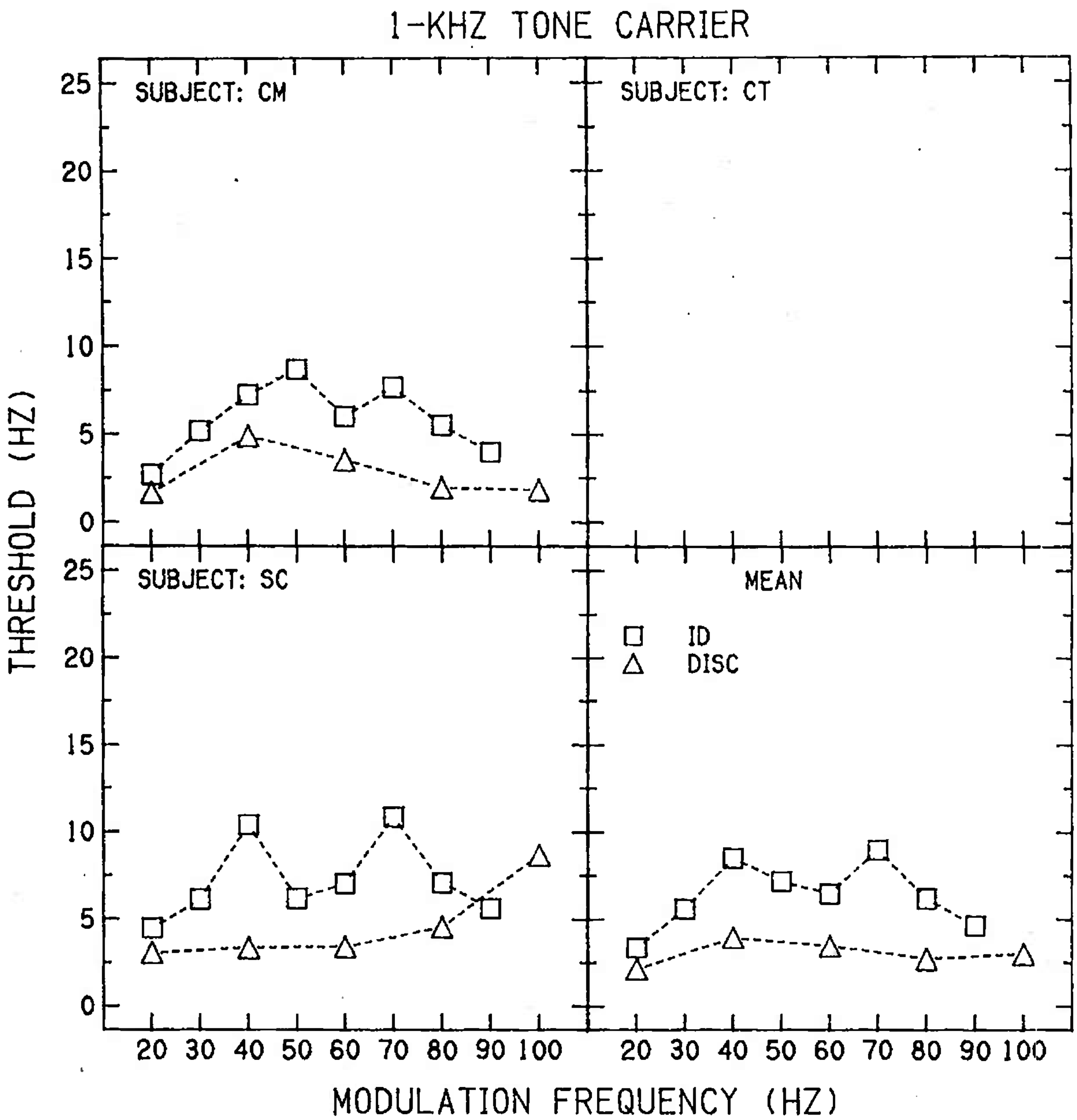

Figure 4a. Threshold, in Hz, as a function of modulation frequency, in Hz, for the discrimination task (triangles) and the identification task (squares) for the 1-kHz tone carrier. The data in Fig. 3a have been converted to obtain the stimulus difference needed to yield a d' of one.

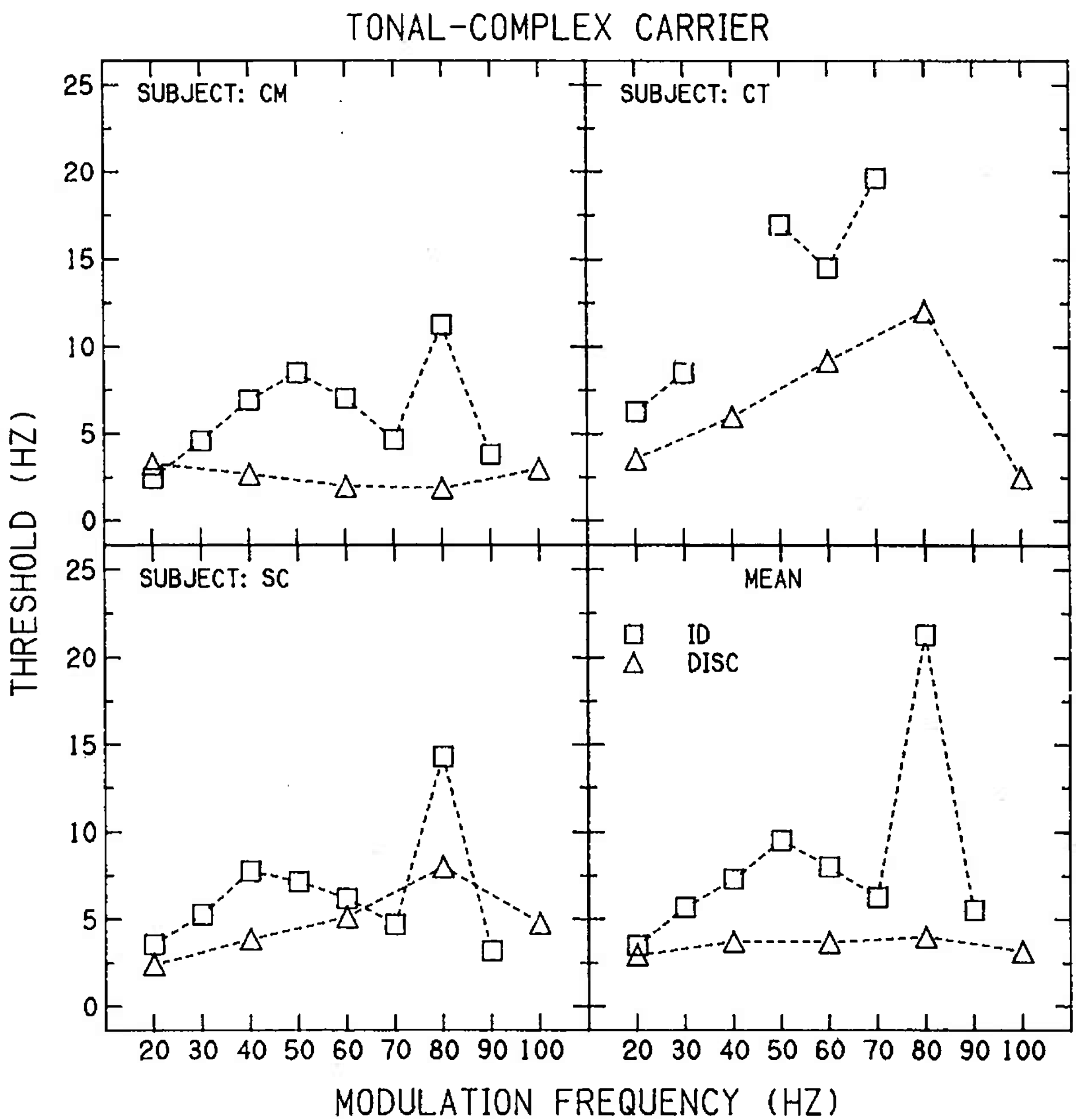

Figure 4b. Threshold, in Hz, as a function of modulation frequency, in Hz, for the discrimination task (triangles) and the identification task (squares) the the tonal-complex carrier. The data in Fig. 3b have been converted to obtain the stimulus difference needed to yield a d' of one.

Finally, it is useful to view these results in terms of the research by Durlach and Braida (Durlach & Braida, 1969; Braida & Durlach, 1972). According to their theory, based on experiments on intensity perception, the discrimination task is limited primarily by sensory (peripheral) noise while the identification task also involves memory (central noise.) The central encoding is governed primarily by the stimulus context, particularly by the range of stimuli. The current results can be compared with those from Durlach and Braida in terms of two measures of the total perceptual range of the stimuli. One measure of the perceptual range of a set of stimuli is the estimated d' between the two extreme stimuli from the discrimination task. This estimate can be obtained by summing d' values from the discrimination task for adjacent stimuli spanning the range of stimuli used in the identification task. For each of the three carriers used in the present research, the cumulative discrimination d' is approximately 24. A second measure, the total resolution in the identification task, can be obtained analogously by summing d' values from the identification task. The cumulative identification d' for each of the three carriers is approximately 12. These two values are similar to those obtained by Braida and Durlach for an intensity range of 30 dB. Thus, for the dimensions of intensity and modulation frequency, a stimulus set with a range of 24 in terms of cumulative discrimination d' results in a total resolution of 12, in terms of cumulative identification d'. In this regard, encoding of modulation frequency is comparable to that of intensity, possibly due to similar central limitations. Moreover, Braida and Durlach showed that further increases in the range of intensities did not increase the cumulative identification d' -- that is, did not increase the total resolution over the range. For ranges of this magnitude, i.e., about 12, the observed resolution of the stimulus set is determined by the context coding mode, providing support to the idea that the observed effects reflect central encoding processes and that the range of frequencies was sufficient to examine memory representation of modulation frequency. Presumably, further increases in the range of modulation frequencies would exaggerate the observed differences in encoding, that is, identification thresholds for mid-range stimuli would increase with the stimulus range, except in the region where roughness or other features permit better encoding.

Study of the effects of stimulus range could provide support for these early conclusions regarding the encoding of modulation frequency and the effect of carrier type. Such a study would determine whether the enhanced resolution for certain stimuli reflects an inherent property of those stimuli or is dependent on the particular context used in the current research. Furthermore, according to the theory proposed by Durlach and Braida for intensity perception, increases in the stimulus range would produce predictable effects on the resolution of stimuli in the set.

ACKNOWLEDGMENTS

This research was supported by the Perceptual Science Program, Office of Naval Research. The help of Susan Carpenter, Cynthia Mitchell, and Christine Thoma for the data collection and analysis is gratefully acknowledged. Also, Drs. Kevin Laxar, Saul Luria, Lynne Marshall, and Jerry Tobias provided valuable comments on an earlier version of this manuscript.

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Naval Personnel R&D Center
1411 South Fern Street
Arlington, VA 22202-2896

Human Factors Branch
Code 3152
Naval Weapons Center
China Lake, CA 93555

Human Factors Department
Code N-71
Naval Training Systems Center
Orlando, FL 32813

CAPT Thomas Jones
Code 125
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Dr. J. Kaiwi
Code 71
Naval Personnel R&D Center
San Diego, CA 92152-6800

Dr. A. R. Susi III
Code 2111
NUSC
New London, CT 06320

LT Dennis McBride
Human Factors Branch
Pacific Missile Test Center
Point Mugu, CA 93042

CAPT W. Moroney
Naval Air Development Center
Code 602
Warminster, PA 18974

LCDR T. Singer
Human Factors Eng. Div.
Naval Air Development Center
Warminster, PA 18974

Special Assistant for Marine Corps Matters
Code 00MC
Office of Naval Research
800 North Quincy Street
Arlington, VA 22217-5000

Human Factors Engineering
Code 441
Naval Ocean Systems Center
San Diego, CA 92152

Mr. Todd Jones
Naval Air Systems Command
Code APC-2050
Washington, DC 20361-1205

Dr. Michael Letsky
Office of the Chief of Naval Operations (OP-01B7)
Washington, DC 20350

Dr. Richard Doolittle
Code 5120
Naval Research Laboratory
Washington, DC 20375-5000

LCDR Thomas Mitchell
Code 55
Naval Postgraduate School
Monterey, CA 93940

Perceptual Science Program
Office of Naval Research
Code 1142PS (3 copies)
800 North Quincy Street
Arlington, VA 22217-5000

Dr. A. L. Slafkosky
Scientific Advisor
Commandant of the Marine Corps
Washington, DC 20380

DEPARTMENT OF THE ARMY

Director, Organizations and
Systems Research Laboratory
US Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Dr. Edgar M. Johnson
Technical Director
US Army Research Institute
Alexandria, vA 22333-5600
21005

Dr. Michael Drillings
Basic Research Office
Army Research Institute
5001 Eisenhower Avenue
Alexandria, VA 22333-5600

Technical Director
US Army Human Engineering
Laboratory
Aberdeen Proving Ground, MD

DEPARTMENT OF THE AIR FORCE

Mr. Charles Bates, Director
Human Engineering Division
USAF AMRL/HES
Wright-Patterson AFB, OH 45433

Dr. J. Tangney
Life Sciences Directorate, AFSOR
Bolling AFB, Bldg 410
Washington, DC 20032-6448

Dr. Kenneth R. Boff
AF AMRL/HE
Wright Patterson AFB, OH 45433

OTHER GOVERNMENT AGENCIES

Defense Technical Information
Center
Cameron Station, Bldg. 5
Alexandria, VA 22314 (2 copies)

Dr. Alan Leshner
Division of Behavioral and
Neural Sciences
National Science Foundation
1800 G. Street, NW
Washington, DC 20550

OTHER ORGANIZATIONS

Dr. James Ballas
George Mason University
4400 University Drive
Fairfax, VA 22030

Dr. Jesse Orlansky
Institute for Defense Analyses
1801 N. Beauregard Street
Alexandria, VA 22311

Dr. James Howard, Jr.
Department of Psychology
Catholic University
Washington, DC 20064

Dr. James A. Simmons
Department of Psychology
Brown University
Providence, RI 02912

Dr. H. P. Van Cott
NAS-National Research Council
(COHF)
2101 Constitution Avenue, NW
Washington, DC 20418